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Implementation and Performance Evaluation of Distributed Autonomous Multi-Hop Vehicle-to-Vehicle Communications over TV White Space

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Abstract—This paper presents design and experimental evaluation of a distributed autonomous multi-hop vehicle-to-vehicle (V2V) communication system over TV white space performed in Japan. We propose the two-layer control channel model, which consists of the Zone Aware Control Channel (ZACC) and the Swarm Aware Control Channel (SACC), to establish the multi-hop network. Several vehicles construct a swarm using location information shared through ZACC, and share route and channel information, and available white space information through SACC. To evaluate the system we carried out field experiments with swarm made of three vehicles in a convoy. The vehicles observe channel occupancy via energy detection and agree on the control and the data channels autonomously. For coarse synchronization of quiet periods for sensing we use GPS driven oscillators, and introduce a time margin to accommodate for remaining drift. When a primary user is detected in any of the borrowed channels, the vehicles switch to a vacant channel without disrupting the ongoing multi-hop communication. We present the experimental results in terms of the time to establish control channel, channel switching time, delivery ratio of control message exchange, and throughput. As a result, we showed that our implementation can provide efficient and stable multi-hop V2V communication by using dynamic spectrum access (DSA) techniques.

Index Terms— ***White space; multi-hop vehicular communication; channel selection, spectrum sensing; dynamic spectrum access***

1 INTRODUCTION

Vehicular networking is expected to be the primary tool to improve traffic flow, and in particular, traffic safety. While various wireless applications are deployed in the vehicle-to-vehicle (V2V) dedicated spectrum, its capacity will become insufficient because of the increased demand. For instance, numerical studies in [1] and [2] point out limitations in capacity of the spectrum dedicated exclusively to V2V safety communications. In [3] we provided examples of emerging vehicle-centric applications, including an open source platform designed for development of such applications. Other wireless communications, such as cell phones, TV broadcasters, data communication, and so on already hold a majority of licensed frequencies. In this situation, the dynamic spectrum access (DSA) paradigm in which unlicensed devices temporarily borrow licensed but spatially and/or temporary unused spectrum called "white space", is a key solution for the spectrum scarcity. At the same time, DSA must ensure that rights of the incumbent spectrum license holders are respected. One method of achieving DSA functionality is cognitive radio (CR), which employs autonomous communication techniques [4,5]. However, most of existing studies on cognitive radio are not adequate for highly mobile ad-hoc vehicular environment, because their architectures and related standards consider network topologies centralized around a base station [6].

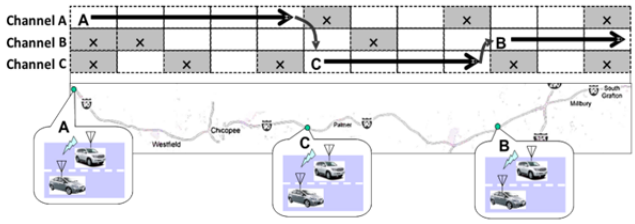

Fig. 1 Concept of the vehicular cognitive network.

We propose to use DSA techniques facilitating utilization of the white space in order to solve inevitable shortage of spectrum problem for vehicular networks. In previous work [7,8], we proposed a distributed autonomous dynamic spectrum management method for the vehicular environment, which enables to establish control channels and subsequent data communication channels and to communicate between multiple vehicles. As illustrated in Fig. 1, this design allows moving vehicles to maintain communication by selecting one of available channels at any time instance. In order to minimize interference to primary users (PUs) which own the spectrum license, one of the indispensable methods is spectrum sensing [3]. Based on the above studies, we carried out the first field test of V2V cognitive communication between two moving vehicles over TV white space, and described the demonstration in [9].

In this paper, we present multi-hop V2V communications over TV white space by extension of the previous work. In order to control multiple vehicles in a realistic environment, we propose the two-layer control channel model. We successfully demonstrated multi-hop V2V

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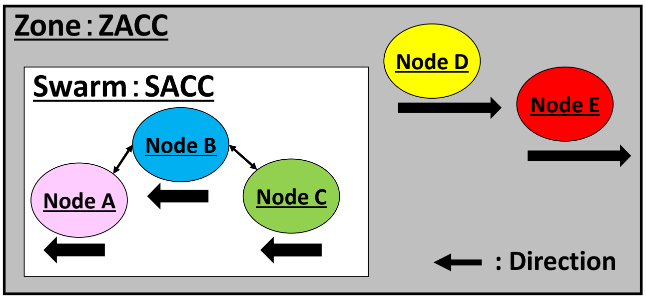


Fig. 2 Two-layer control channel model.

communication in the field experiments presented in [10]. The main component of the experimental hardware on which we implemented algorithms for V2V communication is Ettus Research USRP N210 software defined radio (SDR) [11]. The experimental software is modified GNU Radio [12].

We first introduce the overview of the communication system in Section 2. The channel management algorithm is described in Section 3, and details of implementation design from the viewpoint of hardware and software are shown in Section 4 and Section 5, respectively. “Fine-tuning” is also included there. In Section 6 we explain the field experiments, and present their results in Section 7. We summarize the paper in Section 8.

2 Overview of the Multi-hop Vehicle to Vehicle Communication System

In order to establish communication between the vehicles in the cognitive radio network, it is important to establish control channels through which the nodes share the state of channels used for data exchange and availability of other channels in the white space. In this section, we present the overview of the communication system.

2.1 Control Channels

We propose the two-layer control architecture, which consists of the Zone Aware Control Channel (ZACC) and the Swarm Aware Control Channel (SACC), presented in Fig. 2. First, the vehicles detect each other by broadcasting their location over ZACC. Then, the vehicles in the proximity construct a communication group called “swarm” and then establish corresponding SACC. After that, the vehicles setup data communication using the information about available channels shared through SACC.

1) Zone Aware Control Channel (ZACC): The vehicles share their current location through ZACC. From this information the vehicles develop awareness about other nearby vehicles which travel in the same direction, and construct a swarm[1] [2]. In Fig. 2, nodes A to E in the same zone communicate to each other through ZACC, and nodes A to C, traveling in the same direction, construct a swarm.

2) Swarm Aware Control Channel (SACC): Vehicles can share information about available channels through SACC. Only vehicles which belong to the same swarm can use the same SACC. For example, in Fig. 2 nodes A to C, which joined the same swarm, communicate over the same SACC. All nodes continuously perform spectrum sensing and exchange information about available channels over SACC. The vehicle which sends application data autonomously decides on a route to the destination vehicle, as well as a data communication channel for individual hops from the set of available channels. Through SACC the vehicles in the swarm also share routing information[3], as well as the selected data channel.

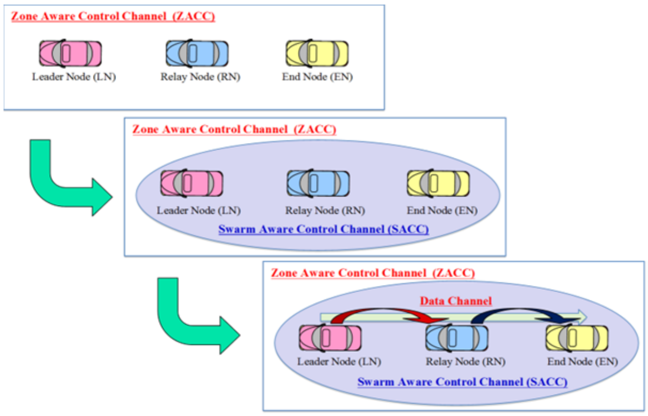


Fig. 3 Procedure of two-hop data communication.

2.2 Data Communication Channels

The data communication channels are selected from the list of available channels obtained through SACC by the vehicle which sends the application data. To simplify medium access implementation on data channels, in case of multi-hop communication we assign different channels to each hop. Therefore, the relay vehicle receives data from the sending vehicle on one channel and forwards it to the receiving vehicle on a different channel.

2.3 Primary User Detection and Channel Switching

If the signal from a primary user is detected, the control channel or data channel communication must be immediately switched to a different channel. The vehicles continuously carry out spectrum sensing to determine channel state and share that information through SACC. Whenever a primary user is detected, information about this event is instantly shared among all communicating vehicles. The vehicles then immediately stop communication on the busy channel and autonomously establish communication on a new channel selected from the set of available white space channels to maintain connectivity.

3 Channel Selection and Switching

As shown in Fig. 3, in our field test three vehicles which travel in the same direction autonomously establish two-hop data communication. Since each vehicle acts as a network node we use terms “node” and “vehicle” interchangeably. We assume an application specific for vehicular networks in which a node having available data selects a route to the destination node based on the information shared over control channels. In the field experi-

[1] Moving speed and direction of each node can be calculated based on the information obtained from multiple (> two) consecutive messages.
[2] Dynamic treatment of vehicle join/leave is out of scope of this paper.

[3] Both “node location” and “list of available channels” are also treated as the routing information, in addition to those for traditional protocols.

ments, three vehicles are in charge of individual roles:

1. Leading vehicle acts as the leading node (LN). It has some application data available for transmission and tries to establish two-hop communication with the end node.
2. Relay node (RN) is the trailing vehicle and forwards the data received from the LN to the end node (EN).
3. End node (EN) is the rear vehicle. It is the intended receiver of the application data transmitted from the LN via the RN.

All nodes periodically transmit information about their current location with timestamps over ZACC, which is a common control channel (CCC) for each zone. Since the nodes receive the same information from other nodes over ZACC, they can all discover their neighbors.

Next, the LN with application data selects the EN as a destination node based on the information shared over ZACC, and forms a swarm of three vehicles (the LN, the EN, and the RN) for achieving efficient two-hop communication. Nodes in the swarm periodically transmit various information including available channels and receive the same information from other vehicles over SACC. In other words, SACC is a CCC for a swarm.

In the implemented system, the transmitting vehicle (LN) decides the route and data channels toward the receiving vehicle (EN). The LN sends the decisions to other nodes using SACC, and then starts multi-hop data communication. Fig. 3 illustrates the sequence of events from "start of control message exchange" until "start of data communication".

After that, data communication may get interrupted frequently due to the primary user appearance on ZACC, SACC, and data channel, and/or the decrease in communication quality. However, the proposed system achieves quick channel switching by exploiting the two types of CCCs to solve these problems.

Next, we describe the procedure until the start of two hop data communication, and explain behavior at channel switching events.

3.1 Procedure until the Start of Two-hop Data Communication

1) Swarm formation based on ZACC communication: Each node periodically broadcasts its own location and ID information over ZACC. The neighboring nodes discover each other through these broadcasts. The nodes obtain the location and time information from the GPS equipment. While periodically broadcasting, the nodes also receive messages from other nodes. Although in practice the frequencies used by ZACC can be occasionaly occupied by a primary user, we assumed for simplicity that predetermined ZACC is free of interruption due to primary user appearance.

The sender node (LN) selects EN as a destination node based on messages received from RN and EN and decides to form a swarm. After that, the LN selects a channel to be commonly used by the swarm as the SACC and sends notification to other swarm members through ZACC. For simplicity, the system selects a channel with the lowest carrier frequency among available channels to serve as SACC. Note that in the realistic environment the available channels change with the movement (i.e., spatial change).

When the RN and the EN receive a request message to form the swarm from LN, they check whether the SACC proposed in the request can be used or not. Then, they start to periodically broadcast the list of available channels over SACC, if available.

2) Data channel establishment based on SACC messages: By using both its own results of wideband sensing (described in Sec. 5.3.2) and the messages exchanged between other nodes on SACC, each node shares available channels among all swarm member nodes. In our system, LN selects a "routing path" and a "data channel for each hop" used for application communication to the EN and disseminates the information on the selection over SACC.

Specifically, the LN first decides a routing path based on sensing results and received SACC messages. Then, it makes a list of available data channels for each hop on the selected routing path. Implemented system selects a different channel for each hop to simplify implementation, that is, to avoid throughput degradation due to co-channel radio interference. Note that radio interference may also occur between neighboring two channels depending on modulation method, and thus our system selects two channels as far as possible from each other.

After deciding on the "routing path" and the "data channels" the LN broadcasts this information over SACC. Other nodes set the "routing path" and the "data channels" for application communication by following this notification. Next, the LN starts two-hop communication after completion of configuration is achieved through the SACC message exchange.

3.2 Procedure for channel Switching

1) Re-establishment of data channel: In the implemented system, the LN takes the initiative in re-establishing data channel, similar to the initial data establishment procedure. Since the primary user (PU) signal may be detected not just by the LN, but by other nodes as well, the data channel switching procedure is different for the following two cases: 1) primary user appearance on data channel for the first hop, which can be detected by the LN; and 2) primary user appearance on data channel for the second hop, which is not detectable by the LN. Note that we assume that the route change caused by the channel switching does not occur in the field tests.

In the first case, since the LN can detect the PU signal directly, it stops data communication on the first hop immediately after detection. After that, the LN decides on a new data channel and informs other nodes about it through SACC. Once the LN receives the confirmation message transmitted from the RN, it restarts data communication.

In the second case a node detecting the PU signal needs to notify the LN in order to initiate decision process for a new data channel. The detecting node stops data communication on the second hop and then transmits the message about the PU detection over SACC. After receiving this notification, the LN determines a new data channel and announces it to other nodes again through the SACC. Other nodes change the data channel to the announced one, and the LN restarts the application traffic after the setup procedures are completed.

2) Re-establishment of SACC: Since the implemented system cannot perform ZACC and SACC communication simultaneously (see in Section 4.3), the nodes normally maintain SACC communication, and switch to ZACC only during initialization and if SACC is interrupted.

If a node detects the primary user signal on SACC, it immediately stops SACC communication and then switches to ZACC communication again. Henceforth, all nodes detecting the primary user re-establish SACC through the same procedures for channel establishment as described in Section 3.1.1.

4 Implementation Design: Hardware

In this section, we present the implementation design of the communication system to achieve "interference reduction" and "antenna sharing" from the viewpoint of hardware equipment.

4.1 GNU Radio/Universal Software Radio Peripheral (USRP)

The main component of the experimental hardware on which we implemented the two-hop V2V communication system is Ettus Research USRP N210 software defined radio (SDR) [11]. The experimental software is modified GNU Radio [12]. Each vehicle consists of "USRP (motherboard + daughterboard)" and "a Management PC connected to USRP via Ethernet cable", in which "Universal Hardware Driver (UHD)" and "GNU Radio" are installed (See Fig. 4).

The USRP mainly supports digital-to-analog (DA) conversion and input-output (I/O) control of radio-wave, and thus allows users to transmit and/or receive packets on different radio frequencies dynamically by overwriting FPGA. Note that complicated processes such as modulation and demodulation are executed on the management PC by exploiting various software library preinstalled in GNU Radio. Furthermore, since several system parameters related to wireless communication, such as communication channel, its PHY rate, transmission power, and so on can be changed by modifying the open-source GNU Radio software, users can freely switch a radio frequency and its modulation/demodulation code without changing hardware system at all.

We implement two sorts of functions of (i) channel selection and switching (for message exchange of control and application data) and (ii) sensing (for keeping track of vacant channels) as software modules of GNU Radio. Note that we employ WBX as a daughterboard loaded on the USRP N210 with the UHD version 3.3.0 and GNU Radio version 3.4.1 in order to implement our proposed functions. The daughterboard WBX supports a wide frequency range of 50 MHz-2.2 GHz, and has two ports: TX/RX port (available for data transmission/reception) and RX port (available for reception only).

1) Implementation method: Since an IP address can be

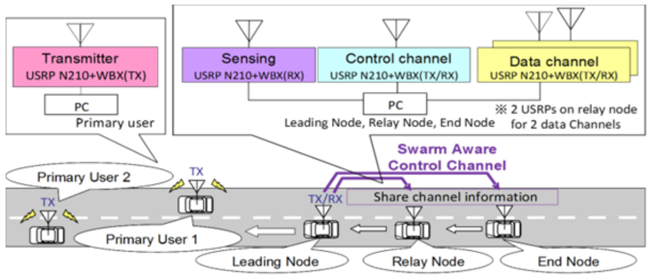


Fig. 4 Hardware components and experimental outline.

assigned to a USRP, the management PC can control multiple USRPs simultaneously by specifying an IP address to an individual USRP. From these distinctive points, our implemented system can execute "application communication over data channel", "message exchange over control channel", and "spectrum sensing" in parallel.

2) Fine-tuning: In our system, since three vehicles perform three different functions in the distributed manner, 10 USRPs (in total) are necessary. Note that the version of firmware for USRP hardware and that of GNU Radio should be unified among 10 USRPs. Moreover, we need to assign an IP address to each USRP unit, so that the management cost of all USRPs could be thus a critical problem in such large-scale experiments. To solve this problem, the management PC should control multiple USRPs efficiently, and we thus unified the network address (prefix) of the IP addresses assigned to multiple USRPs connected to the management PC. From this, in our implemented system, the management cost can be reduced effectively.

4.2 Restriction on the number of onboard antennas

1) Implementation method: Although message exchange over wireless is inherently necessary in V2V communication, a reckless increase of on-board antennas is not feasible due to drawbacks in terms of designability and cost phase. On the other hand, if one antenna is shared by multiple RF front-ends (e.g., USRP), performance degradation such as decrease in transmitted signal power could occur. Hence, the number of on-board antennas should be the minimum number enabling the required functions.

Our implemented system employs an architecture in which each function of "control channel communication", "data channel communication", and "spectrum sensing" is provided by a dedicated USRP. Here, since control information such as a list of vacant channels should be shared among all vehicles in the swarm, a channel commonly available among them should be selected as the control channel. As a result, one USRP needs to manage both of the functions of "control packet" transmission and its reception.

On the contrary, as stated before, we assign a different channel to each hop for data communication, thereby simplifying medium access implementation in case of multi-hop communication. Therefore, the RN is equipped with two USRPs (one for "data packet" transmission and another for "data packet" reception), while the LN and the EN are equipped with just one USRP for data transmission or reception. Furthermore, one USRP is dedicated for wideband sensing (described in Sec. 5.3.2),

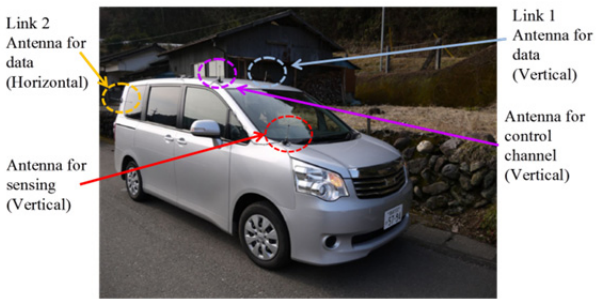


Fig. 5 Antenna setting at RN.

which always cycles over all channels to keep track of vacant channels within the cognitive-ready bands.

Thus, for the LN and the EN, a total of three antennas are loaded with a vehicle, when one USRP occupies one antenna. On the other hand, for the RN, a total of four antennas (USRPs) are necessary. The antennas are set at the RN as shown in Fig. 5.

2) Fine-tuning: In such cases, interference mitigation by selecting antenna polarization is essential. Different assignment of frequencies to different data hops (LN to RN and RN to EN) provides simplicity to the media access protocol (MAC) of each hop. Since the transmission timing control is also independent in two hops, the RN can receive data packet on the first hop while the second hop packet transmission is active. Although different frequency is used on each of hops, large side lobes of the transmitter may affect the adjacent channels at the receiver because the antennas for both hops are practically collocated on the RN. Thus, severe near-far problem occurs although the hops are not on the same channel. In order to reduce interference between transmissions on different hops, the antenna polarization for the first hop and the second hop differs by 90 degrees. The antenna setting at the RN used in the experiments is shown in Fig. 5. One antenna is dedicated for the control channels, two more antennas are used for data channels (one for transmission and one for reception), and the fourth antenna is intended for sensing. Among these antennas, only the antenna for the second data hop is horizontally polarized. All other antennas are vertically polarized. As a result, crosspolarization mitigates the interference between the transmitter and the receiver at the RN.

4.3 Antenna sharing for control channels

1) Implementation method: Simultaneous use of two control channels with different frequencies generally requires two separate antennas. However, besides two control channels, the RN already needs three more antennas, used for sensing and communication on two data channels. For simplicity one transceiver and its antenna are shared by both control channels. They are used for ZACC communication until the formation of a swarm. After the establishment of SACC, they are used for SACC communication. When the SACC communication is interrupted after primary user detection, and needs to be reestablished on a different channel, the same antenna is used for ZACC communication again. However, in practical wireless environment, since both a location of each vehicle and its moving velocity could be drastically varied, it will happen that some nodes cannot detect the primary signal on SACC and thus cannot switch to the ZACC immediately. As a result, the node which detected the primary user cannot inform other nodes using ZACC.

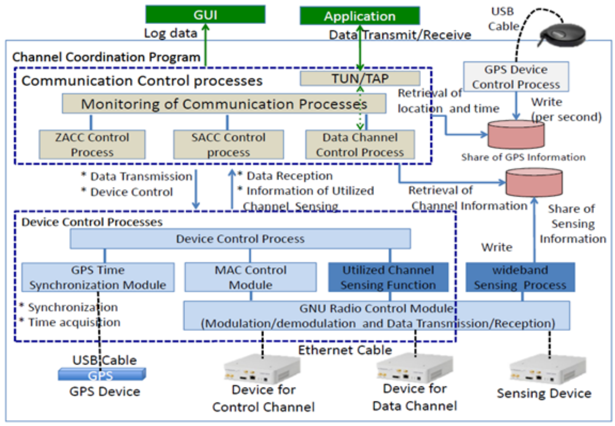


Fig. 6 Architecture for sync. between multiple processes.

Therefore, the implemented system employs a timeout scheme by utilizing the periodicity of SACC transmissions. When other nodes detect interruption in communication on SACC by experiencing this timeout, they stop SACC communication immediately, and switch to ZACC communication again.

2) Fine-tuning: As stated in Section 4.3.1, our implemented system dynamically selects a channel for control message exchange from two sorts of control channels (i.e., ZACC and SACC) in response to the communication condition. However, our original implementation design employs an architecture in which ZACC communication and the SACC communication are performed simultaneously. Therefore, we assume a case where communication over the ZACC and the SACC are performed simultaneously, and thus each function of ZACC/SACC communication was implemented as an individual process. Eventually, these two functions are implemented in a way to enable not only the related processes to be synchronized but also the wireless resources to be shared. Details of the multi-process management are described in Section 5.2.

5 Implementation Design: Software

Here, we present the implementation design of the system to achieve “spectrum sensing”, “MAC protocol”, and “route/channel decision” from the viewpoint of software.

5.1 Communication System

Wireless communication system sharing one dedicated radio frequency typically employs Half-Duplex way similar to Wireless LAN. From this, we first tried to implement the half-duplex system.

1) Implementation method: Python library in GNU Radio supports two kinds of functions of “data transmission process consisting of modulation and transmission to USRP” and “data reception process consisting of reception from USRP and demodulation” as different threads. Therefore, half-duplex communication can be achieved in a straightforward way to start and stop these two threads by turns synchronously. However, we observed a critical issue that, in current GNU radio/USRP platform, both threads cannot be restarted once after they are stopped.

From this, we next tried to effectively use the TX/RX port described before without executing the stop of both threads. However, when these two threads are run in parallel, we recognized the fact that the TX/RX port is automatically devoted to data transmission. Moreover, the RX port is automatically devoted to data reception. That is, the USRP with the TX/RX port and the RX port automatically provides Full-duplex communication, so that we needed to develop the half-duplex implementation even under the platform with a function of Full-Duplex communication.

2) Fine-tuning: Simultaneous use of two ports on WBX is essential, but just one antenna is allocated to USRP+WBX unit due to the limitation of the number of on-board antennas. Therefore, our implementation utilizes a "signal distributor" to share one antenna between two ports.

However, in such cases, since the signal emitted from TX/RX port inevitably reaches the RX port without experiencing attenuation, the circuit will be likely to break down. Then, when a "signal splitter" is used instead of the signal distributor, we measured the received signal at the RX port by using spectrum analyzer and observed that the received signal remains still higher (i.e., attenuation is not good enough). Therefore, we inserted an attenuator between the TX/RX port and splitter. In this way, we emulated the half-duplex system over the full-duplex platform, but implementing of the half-duplex system on the GNU Radio/USRP platform is not developed yet.

5.2 Synchronization of multiple processes

In our implementation, each vehicle independently performs three different functions of "communication over the control channel", "communication over the data channel", and "spectrum sensing" each of which occupies a USRP unit.

1) Implementation method: Our implemented system establishes three individual processes to provide the three functions (management of "the control channel", "the data channel", and "the spectrum sensing"). Although functions of "the data channel" and "spectrum sensing" are able to occupy one USRP unit, a function of "control channel" requires to use two sorts of control channel (ZACC/SACC) logically on a USRP unit in a time division manner. On the other hand, in our original implementation design, these two functions are assumed to be performed independently. Therefore, in the system, each of functions is implemented as a different process, but can also be performed in the synchronized manner through the architecture, as shown in Fig. 6.

2) Fine-tuning: Our implemented system needs to achieve not only "simultaneous use of multiple processes" but also "sharing of a hardware equipment". More specifically, although each of ZACC/SACC processes needs to share one USRP, the USRP refuses an access from multiple processes. To solve this, we additionally prepare a process used for operation of the USRP, and thus ZACC/SACC processes can share the USRP via the process for USRP operation. Furthermore, to achieve a "interprocess communication", we employed a UNIX socket that can share resources between processes. As a result, ZACC/SACC communication in time division manner can be achieved.

5.3 Sensing

1) Overview of the Spectrum Sensing: The role of the spectrum sensing in this system is twofold. First, spectrum sensing is used to confirm vacancy of the communication channels which are to be adaptively utilized by the cognitive vehicular network secondary users (SUs). We denote this type of sensing as the "utilized channel sensing". The second purpose of spectrum sensing is to keep track of vacant channels which can be used as backup when the current communication channel is determined to be occupied by a primary user. This type of sensing is termed "wideband sensing".

The utilized channel sensing runs on the data and control channels alternately with communication between the nodes. In order to achieve sufficient detection sensitivity, the communication among SUs is terminated during the sensing period. On the other hand, in order to sense multiple channels during a short time, the wideband sensing continuously senses all channels and stores the sensing results in memory of each node even when the data and the control communication are active. As a result, rapid channel switching can be realized when a primary user is detected. These two types of sensing enable secondary users to detect an active PU and continue communication by smoothly switching to a vacant channel without generating interference to the PU.

a) Fine-tuning: In this field test the nodes have multiple transceivers for different functions: one for control, one (LN and EN) or two (RN) for data communication, and one for wideband sensing. Since the utilized channel sensing is operated on each control and data channel, this sensing function is implemented in the corresponding control and data transceivers.

In order to avoid the influence of communication between SUs, a reserved period for sensing called quiet period (QP) is introduced. During this period, all SUs simultaneously terminate transmission and use quiet period for reliable PU detection. In this system we implemented energy detection method. It is a simple method, used both for the wideband sensing and the utilized channel sensing. It detects existence of the primary signal by comparing the averaged power of the received signal samples with a predefined threshold [13]. Our implementation uses N = 2048 samples collected with 2 MHz sampling rate. If we denote the nth sample of the received signal as $x(n)$, the detection algorithm is given by

$$\frac{1}{N}\sum_{n=1}^{N}\left|x(n)\right|^2 \underset{<}{>} \gamma : \begin{array}{l}\text{PU is ON}\\ \text{PU is OFF,}\end{array} \tag{1}$$

where γ represents the detection threshold. We set the sensing threshold γ = -100 dBm as the arithmetic mean of the average PU signal power and the noise floor. We experimentally confirmed that no missdetections occurred during 10^5 sensing trials with the above parameters, indicating that the prob. of missdetection is $P_M = 1\text{-}P_D < 10^{-5}$. Repeating the same experiment with the primary transmitter turned off results in the false alarm rate $P_{FA} < 10^{-5}$.

The decision algorithm (1) is used for the wideband

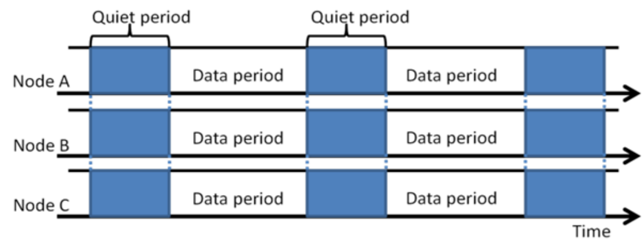


Fig. 7 Time Synchronization for utilized channel sensing.

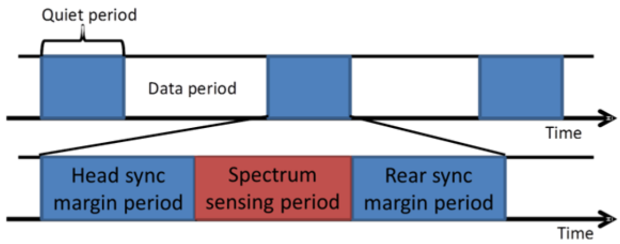


Fig. 8 Design of quiet period for the sensing system.

sensing and the utilized channel sensing.

2) Wideband Sensing: In order to switch the communication channel when the PU is detected, either during communication, or at the initiation of communication, each node has to always know the current channel status. To that goal the wideband sensing transceivers on all nodes cycle over all channels. Each PC which serves as a network node updates the table stored in its memory with sensing results. This table is updated as soon as the cycling over all channels is completed (approx. 280 ms). Conveniently, since energy detection as a blind method does not discriminate PUs from SUs, the channels used for communication and control are wrongly reported as busy even if only SU signal is transmitted on each channel. Moreover, since the wideband sensing is not synchronized with QPs of the utilized channel sensing, the SU's transmission sidelobes may be falsely interpreted as a PU occupying the adjacent channels, provided that the SU's power is sufficiently strong at the sensor. Indeed, this is the case for the secondary transceiver and the sensor placed on the same vehicle because of small distance (with respect to the wavelength) between their antennas.

a) Fine-tuning: Here, in order to avoid the detection of SU signal in the same channel, the wideband sensing ignore the sensing results of the current communication and control channel in active. The PU signal is detected on the active channels by using utilized channel sensing with quiet period as shown in the next subsection. To mitigate the effect of large power leaking into adjacent channels on the same vehicle, the sensing antennas are positioned to the non-line of sight (NLOS) location with respect to other antennas, as shown in Fig. 5. This simple manipulation provided sufficient margin to isolate the sensor from the practically collocated secondary transmitter(s) without sensing performance degradation. Here, the vertical polarization is used for wideband sensing.

3) Utilized Channel Sensing and Quiet Period: The utilized channel sensing periodically checks status of the primary signal on the control and data exchange channels. In order to distinguish the primary signal from the secondary's own signals, the sensing period of all secondary users must be synchronized, as illustrated in Fig. 7. If a signal is detected during the quiet period, the node perceives that the primary user is active, and starts the channel switching process. Time synchronization among nodes is achieved with GPS driven oscillators.

a) Fine-tuning: We adjusted the quiet period parameters empirically. The optimal quiet period duration for energy detection which results in the largest throughput has already been studied in [14, 15]. In these simulation-based studies perfect time synchronization is assumed between multiple nodes. However, in experiments, although the node clocks were synchronized using GPS driven oscillators (GPSDO), the synchronization error was significant enough to require a time margin to avoid false primary user detections (Fig. 8). Any secondary transmission during a quiet period, which is out of synchronization due to the clock offset, would be interpreted as a primary user transmission by energy detection. If spectrum sensing is started as soon as the data communication finishes, other nodes might still be continuing data communication which causes a false alarm. False alarm might also occur if data communication is instantly started after the sensing period. On the other hand, to achieve higher throughput, quiet period should be selected as short as possible.

To estimate the minimum sync margin period sufficient to avoid false alarms, we carried out a simple experiment. Two vehicles exchange data during data periods (DP), and perform sensing during quiet periods. The GPS based clock synchronization is executed periodically at the time instance when the DP begins. One cycle of QP and DP is fixed to 1 s. This value is selected because it provides sufficient spatial resolution. A car traveling even at an excessive speed of 160 km/h moves less than 45 m during each sensing interval, which is the distance comparable to the requirements for mobile sensors imposed by the Federal Communications Commission (FCC) [16] and the IEEE 802.22 standard [6]. The start of quiet period is used as the reference point (0 ms). Then, the initial value of the head sync margin period and the rear sync margin period (Fig. 8) are set to 100 ms. While it takes 1 ms to collect samples for averaging described in (1), it takes around 40 ms to process the samples and reach the decision. To be on the safe side, the initial value of DP start time is set to 260 ms.

First we decrement the head sync margin in 10ms steps, and check whether sensing can be carried out without false alarms during 300 s. This experiment results in the minimum sync margin of 50 ms. Next, we decrement the DP start time in 10 ms steps to obtain the minimum DP start time of 100 ms. Moreover, in the same experiments involving three vehicles during 300 s with the same parameters we did not observe any false alarms. Consequently, we set the timing to the 100 ms quiet period (consisting of 50 ms head sync period, 40 ms of actual sensing and 10 ms of rear sync period), and the 900 ms data period which makes up for the rest of 1 s period.

5.4 MAC protocol implementation

In the implemented system, since we assume a unidirectional application from the LN to the EN, frame collision over data channel at each hop never occurs. On the other hand, message transmission on the control channel

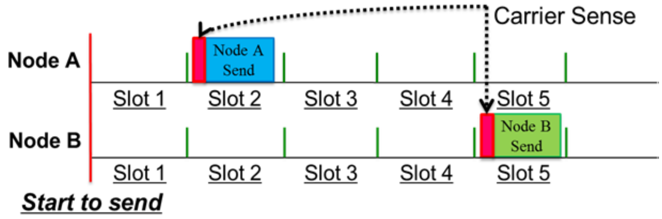


Fig. 9 Concept of implemented MAC.

can simultaneously start on more than one node. If, for instance, two nodes detect a PU, they might attempt to broadcast that information at the same time. Therefore, frame collisions could occur on the control channels, and thus, a MAC protocol dealing with collisions is necessary.

1) Implementation method: GNU Radio provides a sample code "tunnel.py" which includes the MAC protocol implementation based on carrier sensing. If a node detects message transmission from another node as a result of "carrier sense" process, it waits for a fixed period and performs carrier sensing again. Consequently, if the nodes try to transmit a message simultaneously, frame collisions will be repeated indefinitely, thereby completely preventing packet reception.

To solve this issue, we implemented a simple MAC that waits for a random period before carrier sensing. If the frame transmission is allowed as a result of carrier sensing, the waiting time is determined by the uniform random number of slots (up to 5) of 1 ms. The concept of simple MAC is shown in Fig. 9.

In Fig. 9, node A waits for a period of 1 slot, while node B waits for a period of 4 slots. The node A performs carrier sensing at the time of slot 2 and then starts to transmit the frame. Node B performs carrier sensing at the time of slot 4, and the transmission process of node A is perfectly completed. As a result, node B can transmit a frame successfully without detection of frames transmitted from node A, thereby avoiding frame collision efficiently.

2) Fine-tuning: tunnel.py provided by GNU Radio/USRP cannot execute continuous carrier sensing like IEEE 802.11 Wireless LAN. Therefore, we employed a random waiting period to distribute the timing of carrier sensing among multiple nodes and implemented a simple MAC like CSMA/CA. However, the random waiting time before carrier sensing is determined by software processing, so that the achievable tick of a slot period becomes relatively longer (i.e., 1 ms). Therefore, implementation of MAC protocol that can provide efficient access control is one candidate of our future works.

5.5 Network application and IP routing for two-hop data communication

1) Implementation method: Since the implemented system employs tunnel.py that can create a TAP device and treat USRP N210 (see the detail in Section 6) attached to the host computer as a virtual Ethernet device, we can allocate IP addresses to all USRPs. From this, we can run a network application at the LN by directing the traffic to the IP address allocated to the EN.

2) Fine-tuning: To simplify the implementation of two-hop data communication system, we allocated different IP subnets between the first hop (from LN to RN) and the second hop (from RN to LN), and predefined static routing tables at LN and EN. This solution provides end-to-end routing by exploiting the IP protocol implemented in the Linux kernel. We show the two-hop communication by using TAP device and IP routing in Fig. 10.

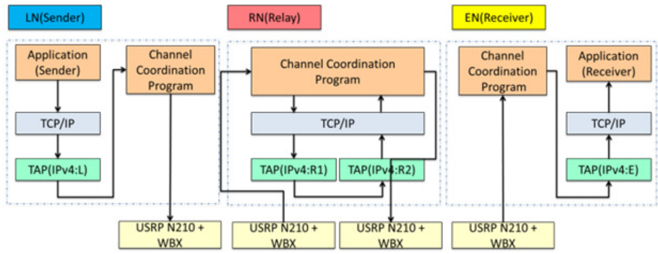


Fig. 10 Two-hop comm. by using TAP dev. and IP routing.

5.6 Improving stability of two-hop data communication

1) Implementation method: In our system, the LN always selects a data channel when necessary. The information of data channel assigned to each hop is included in some messages and is broadcast over SACC. Besides, in terms of PU detection, we also can consider the following two cases: the primary signal is detected by (i) the LN and (ii) other nodes (except for the LN). In particular, in the second case, a node detecting PU signal needs to inform it to the LN over the SACC.

In practical environment, however, the control messages broadcast over SACC may not be received by all nodes of a swarm successfully, depending on wireless environment and the distance from the LN (The EN can be far away from the LN). In such cases, the information of a data channel for each hop may not be shared among nodes, which unfortunately may result in the same data channel being used on both of the neighboring two hops. This would cause the radio interference.

2) Fine-tuning: To avoid the throughput performance degradation due to co-channel radio interference, the LN selects two separated channels whose center frequency are separated by more than 2 MHz. More specifically, the LN sequentially decides a data channel, i.e., a data channel for the hop between the LN and the RN is firstly determined and then that for the hop between the RN and the EN is determined.

Furthermore, we added a new function to share the information of "routing" and "data channels" reliably among all nodes through message exchange over SACC. If the information broadcast from the LN cannot reach the EN successfully, the information of "routing" and "data channels" are not consistent between the LN and the EN. To avoid this inconsistency, we added a function to allow the RN to certainly re-broadcast only the messages including the information of "routing" and "data channels".

6 Field Experiments

Figure 4 outlines the experiments with three moving vehicles. Different USRP units on each vehicle are used for: 1) communication over the control channel; 2) communication over the data channel; and 3) spectrum sensing. To control the programmable radios, a desktop computer

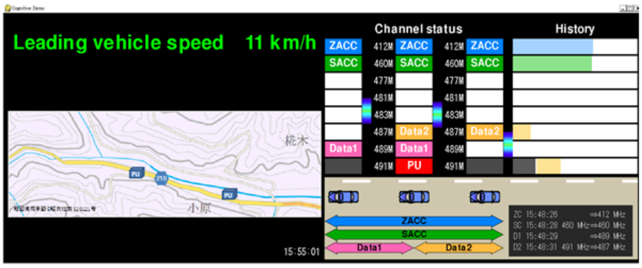


Fig. 11a Speed/break display. Fig. 11b Channel info. display.

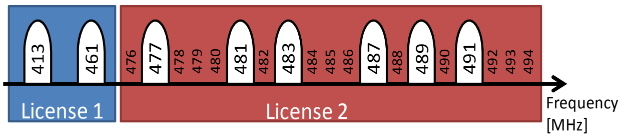


Fig. 12 Channel assignment for the experiments.

with network cards is placed in each vehicle. The desktops run custom applications which are modifications of the open-source GNU Radio software. As the three vehicles move together, the information on the speed of the leading vehicle is transmitted to the rear vehicle through the relay vehicle. When the leading vehicle suddenly breaks a picture of the road in front is taken by the on-board camera. The leading vehicle then transmits the picture in addition to the current speed. In the rear vehicle, this information is presented on a monitor (Fig. 11a). On a separate monitor in the rear vehicle information about the channel availability and usage is displayed (Fig. 11b).

The experimental license we obtained from the Ministry of Internal Affairs and Communications was valid for channels which are out of the coverage contours of local TV broadcast stations (i.e. not used) at the experimental site. For that reason we used two stationary USRPs on vehicles parked by the road to emulate primary users. When the moving three-vehicle swarm approaches one of emulated primary users, the vehicles switch to a vacant channel after detecting the primary user signal, as illustrated in Fig. 4.

The experiments were carried out in Misato Town, Miyazaki, Japan in Jan. and Feb. 2012. We applied for permission to use three 6 MHz wide TV channels from 476 to 494 MHz which are unused in the Misato area. Since we needed more than three channels for the experiments, we split the allocated bandwidth into 1 MHz channels and used six channels. Two additional 1 MHz channels, centered at 413 and 460 MHz, were made available to us through the special experimental spectrum license for Kyushu area. Overall, we used eight 1 MHz channels (Fig. 12). The spectrum licenses are detailed in Tables I and II. In order to limit out-of-band emission we were allowed to use only certain modulations.

7 Results and Discussion

In this section, since a) the latency for channel establishment and switching, b) the delivery ratio of SACC messages, and c) the antenna polarization and the channel separation deeply affect the throughput performance of the proposed system, we examine its performance from the view point of a), b), and c).

TABLE I
Local experimental radio license.

License duration	Mar. / 31st / 2012
Region	Misato Town, Miyazaki, Kyushu Region
Center Frequency	477,480,481,483,486,487,489,491,492 MHz
Antenna Power	40 mW (16 dBm)
Modulation	GMSK , DBPSK , DQPSK

TABLE II
Regional experimental radio license.

License duration	Oct. / 31st / 2013
Region	All Kyushu Region
Center Frequency	282.6 , 412.9725 , 428.2 , 460.75 MHz
Antenna Power	40 mW (16 dBm)
Modulation	GMSK , DBPSK , DQPSK

TABLE III
System parameters for experiments.

Modulation scheme	GMSK
PHY rate	1 Mbps
Threshold for Utilized channel sensing	-100 dBm
Threshold for Wideband sensing	-100 dBm
QP: Total duration (Head sync/Decision making/Rear sync)	0.1 s (0.05/0.04/0.01)
Data transmission period	0.9 s
ZACC message interval	1s
SACC message interval	0.1/0.3/0.5 s
SACC timeout	5 s
Iperf: UDP transmission rate	1 Mb/s
UDP packet length	1480 byte
Distance between neighboring cars	15-25 m
Vehicle velocity (mobile env. only)	20-30 km/h

7.1 Evaluation of the Channel Management System

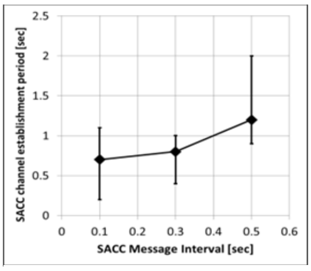
Table III shows the experiment settings. We use Iperf [17] to send UDP traffic from the LN to the EN via the RN, and examine the following two criteria:

- *Channel establishment period:* is the time interval from "the ZACC establishment" to "the data channel establishment". This evaluation is performed with stationary vehicles (not in a mobile environment).
- *Channel switching period:* is the time interval from "the detection of primary user signal" to "the SACC and data channel reestablishment". This evaluation is performed in a mobile environment.

Since a SACC message interval deeply affects these two kinds of periods, we investigate how these periods are varied with the change in the SACC message interval. The experiments are repeated five times to obtain their max/avg/min values.

1) Channel establishment period: We break the channel establishment period into two parts: 1) SACC establishment; and 2) data channel establishment. Fig. 13 shows the strong dependence on SACC message interval. It also indicates max. and min. of five times measurements.

As described in Sec. 3.1.1, the SACC establishment period consists of the sequence of events: i) the LN receives ZACC messages from the RN and the EN; ii) the LN sends a notification message of SACC over ZACC and then iii) receives messages transmitted from other nodes over SACC. Note that although ZACC messages and



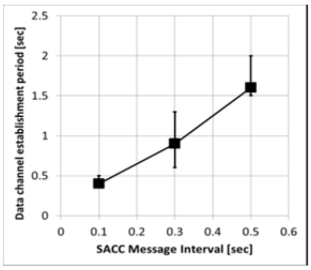


Fig. 13a SACC establishment. Fig. 13b Data channel establishment.

SACC messages are periodically transmitted from all nodes in the synchronized manner, our implemented MAC tries to avoid packet collisions. As a result, one SACC interval and processing delay (approximately 100 ms) for frequency change (from ZACC to SACC) are, at least, necessary for the SACC establishment.

Next, as described in Sec. 3.1.2, the data channel establishment period is a sum of the times needed to execute the following message exchanges over SACC: iv) the LN sends one notification message about the data channels assigned for each hop; and v) the LN confirms that other nodes completed the channel setting process. That is, two SACC intervals are necessary.

Since it takes a relatively large time to change frequencies due to software processing, the SACC establishment period indicates relatively larger value (but less than 1 s) with the SACC interval of 0.1 s, as shown in Fig. 13.

2) *Channel switching period:* Figure 14 illustrates the channel switching experiments. At ①, ②, and ③, the primary signals appear on the data channel for the first hop, on the data channel for the second hop, and on the SACC, respectively. Experimental results in terms of channel switching are shown in Table IV.

*a) **Data channel switching:*** As described in Sec. 3.2.1, the data channel switching procedure is different for two cases: (1) the LN detects the primary signal; and (2) the RN or the EN detects it. In the former case, (i) the LN decides a new data channel and informs other nodes about it through SACC; and then (ii) the LN receives a SACC message transmitted from the RN. That is, two SACC messages (intervals) are necessary. In contrast, in the latter case, (iii) a node detecting the primary user signal needs to notify the LN in order to initiate decision process for a new data channel. So, the total of three SACC messages (intervals) is needed.

The results in Table IV present the time needed to switch to a new data channel for both cases. It should be noted that "lower bound" simply indicates the time required for two SACC messages exchange (the former case) and that for three SACC messages (the latter case), respectively. From this table, we can see that the min. values are close to the lower bound and the avg. values are somewhat larger than the lower ones, with any SACC message intervals. In a real environment, SACC messages are lost frequently on the wireless link, but our implementation needs to wait the next timing for retransmission. Furthermore, periodical communication interruption due to sensing period is inevitable. These two main factors directly increase the data channel switching time.

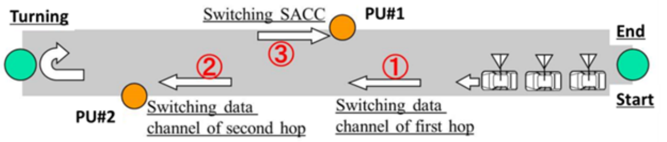


Fig. 14 Channel switching experiments.

TABLE IV
Channel switching time.

SACC msg. interval [s]	Lower bound [s]	Min. [s]	Avg. [s]	Max. [s]
Data channel switching time when LN detects the PU				
0.1/0.3/0.5	0.2/0.4/0.6	0.4/0.5/0.7	0.7/0.9/0.9	1.2/1.5/1.2
Data channel switching time when RN or EN detects the PU				
0.1/0.3/0.5	0.3/0.7/1.1	0.5/1.2/1.2	0.9/1.5/1.6	1.5/1.8/1.7
SACC switching time				
0.1/0.3/0.5	1.2/1.4/1.6	1.4/2.5/2.2	5.6/6.6/6.4	11/10/11

*b) **SACC switching:*** As described in Sec. 3.2.2, if nodes detect the primary user signal on SACC, the nodes stop SACC communication immediately, and then switch to ZACC communication again due to the antenna sharing (see in Sec. 4.3). After that, all nodes detecting the primary user re-establish SACC through the same procedures for SACC channel establishment (see in Sec. 3.1.1).

In this case, in addition to the SACC channel establishment period (described in Sec. 7.1.1), one ZACC interval is needed. As shown in Table III, since the ZACC message interval is 1 second, SACC switching time is larger than 1 second. Moreover, the LN needs to wait for two ZACC messages transmitted from the RN and the EN to initiate the SACC re-establishment process, so that the waiting time clearly increases the SACC switching time.

In the mobile environment, transmitted messages will be likely to be lost frequently due to various effects. In this case, our implementation needs to retransmit messages after a message interval. Furthermore, if there is a node that cannot detect the primary user signal, it must wait for the SACC timeout to initiate the SACC re-establishment process. Since both ZACC interval and timeout values are large, the switching latency is drastically increased in the worst case.

From these results, we can conclude that our implementation with short SACC message interval can quickly switch the SACC and the data channel after the primary user signal is detected. That is, the proposed implementation has a potential to be adequate for practical use at a cost of increased control messages.

7.2 Delivery ratio of SACC message exchange

Since the performance of data communication heavily depends on the control messages periodically broadcast over SACC, we investigate the delivery ratio of SACC messages for every node pairs, when the message intervals are varied from 0.1 s to 0.5 s. The ratio is calculated as follows,

$$Ratio = \frac{Num\ .of\ \ RX\ \ pkts\ \ (at\ \ receiver\ \ node\ )}{Num\ .of\ \ TX\ \ pkts\ \ (from\ \ sender\ \ node\ )} \qquad (2)$$

Fig. 15 illustrates the delivery ratio of SACC message exchange for every node pairs. From this figure, we can see that the ratio of pair <LN- EN> and <EN-LN> is clearly lower than those of other pairs, irrespective of the

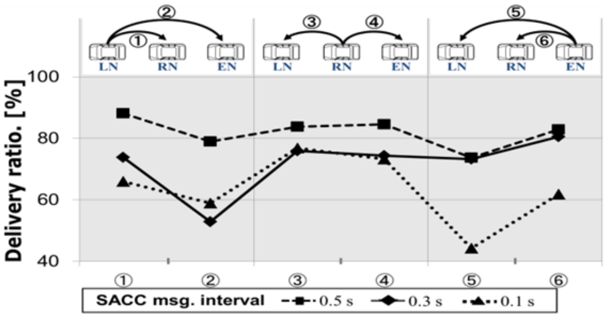


Fig. 15 Control message exchange ratio.

SACC interval. That is, reliable SACC message exchange between end-nodes (i.e., LN and EN) cannot be always provided. In the experiments performed, it is likely that the radio propagation condition changed due to obstacles on tight curve and slope. Moreover, since the short SACC intervals leads to relatively low delivery ratio, we can see that the simple MAC protocol (described in Sec. 5.4) with long slot period (i.e., 1 ms) causes congestion and frequent frame collisions.

From these results, under the practical environment, the control message delivery ratio between end nodes is notably decreased due to both the variation of radio propagation environment and short intervals of control message transmission. As a result, we can confirm that a function of re-broadcasting the information of "routing" and "data channels" (described in Sec. 5.6) plays an important role to provide stability of two-hop data communication even under the severe network condition.

7.3 Throughput

From the practical use point of view, the data throughput is drastically changed due to the antenna polarization and the channel separation. Therefore, as a basic test, throughput of the single-hop communication was examined between two stationary vehicles. The distance between the vehicles was set to 20 m. In the second test, we measured throughput of the two-hop communication between three stationary vehicles with varying antenna polarization and varying center frequencies. Note that we used either the same polarization or cross-polarized antennas on both hops. The data packets were exchanged over 1 MHz channel, with bitrates set to 1 Mb/s. Here, as a preliminary experiment, we generated a continuous UDP stream by Iperf and did not consider both the channel sensing overhead and the medium access overhead to obtain the upper bound on the achievable maximum throughput. For each parameter setting we keep sending data packets for 300 s, and compare UDP throughputs.

The results are summarized in Table V. From this table, we can see that although the UDP throughput in the single-hop case is 954 Kb/s, the throughput in two-hop communication with 2 MHz or larger separation of carrier frequencies between the data channels is almost the same, irrespective of antenna polarization. On the other hand, the throughput with 1MHz separation between center frequencies is drastically degraded due to interference caused by out-of-band leakage. However, in this case, the cross-polarized antennas on different data channels

TABLE V
Measured throughput

Num. of Hop	Polarization		Carrier separation [MHz]	Throughput [Kb/s]
	LN->RN	RN->EN		
Single	Vertical	----	----	954
Two	Vertical	Horizontal	3	952
	Vertical	Vertical	3	954
	Vertical	Vertical	2	952
	Vertical	Horizontal	1	326
	Vertical	Vertical	1	136

provide throughput of approximately 2.4 times higher than that for the same polarization on both data channels.

From these field experiments, we can demonstrate that both the cross-polarized antennas and the channel separation with more than 2 MHz separation between the data channels are crucial to improve the throughput performance from the practical point of view. Therefore, we use two separated channels (more than 2 MHz) in Sec. 5.6.

8 Conclusion

Vehicular networking is expected to become widely used to enhance traffic safety and travel experience. The white space will be a good resource to dynamically provide necessary bandwidth for various applications with the possible exception of safety-related applications. In this paper we presented the field experiments of the multi-hop V2V communications over TV white space. In order to establish the cognitive distributed network autonomously we implemented the communication protocol with three components on GNU Radio/USRP platform: 1) the two-layer control channel subsystem; 2) the multi-hop data communication subsystem; and 3) the spectrum sensing and channel switching subsystem which protects primary users from interference. Then, we examined the system performance in terms of (a) channel establishment period, (b) channel switching period, (c) delivery ratio of control message exchange, and (d) achievable throughput, when the primary user signal is detected. Through the experiments, we showed that our implementation can bring quick channel establishment and switching by exploiting frequent SACC message exchanges. Moreover, re-broadcast of control message, the antenna polarization, and the channel separation drastically improve the throughput performance. Finally, we have shown that our implementation can provide efficient and stable multi-hop V2V communication by using DSA techniques.

One direction for future work is to design and implement a new MAC protocol suitable for vehicular cognitive networks. Then, a way of reducing control message overhead is the second topic of our future research.

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